Relativistic Atomic Physics: from Atomic Clock Synchronization towards Relativistic Entanglement.

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Abstract

A review is given of the implications of the absence of an intrinsic notion of instantaneous 3-space, so that a clock synchronization convention has to be introduced, for relativistic theories.

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The recent developments in the construction of microwave and optical clocks in atomic physics are opening a new era in clock synchronization [1]. The proposed ACES mission of ESA, if accepted, will make possible a measurement of the gravitational redshift of the Earth from the two-way link among a microwave clock (PHARAO) on the Space Station and similar clocks on the ground: the proposed microwave link should make possible the control of effects on the scale of 5 picoseconds. This will be a test of post-Newtonian gravity in the framework of Einstein's geometrical view of gravitation: the redshift is a measure of the $1/c^2$ deviation of post-Newtonian null geodesics from Minkowski ones. This is going to create problems to relativistic metrology (the standard of time will have to be put in space to avoid the local variations of the geopotential) and will open the possibility of relativistic geodesy for formulating a theory of heights over the reference geoid.

The problem of clock synchronization is equivalent to the problem of the definition of an instantaneous 3-space (all its points are synchronous), which in turn is a prerequisite for the definition of a well-posed Cauchy problem for field equations like the Maxwell ones, i.e. for the predictability of the future.

In Galilei space-time both Newtonian time and the Euclidean 3-space (with the associated notion of spatial distance) are *absolute* so that the problem of clock synchronization does not exist in either inertial or non-inertial frames. The inertial ones, connected by Galilei transformations, are an ideal limit selected by Newton law of inertia and by the Galilei relativity principle: in them Newton's equations are invariant in form. The apparent forces of non-inertial frames are proportional to the inertial mass, which in turn is equal to the gravitational mass (the Galilei equivalence principle). Non-relativistic quantum mechanics, with its foundational problems, and the theory of entanglement are formulated in this framework where Maxwell equations do not exist. The photons in the discussions about entanglement and teleportation are only states with two polarizations in a two-dimensional Hilbert space: their carrier cannot be a ray of light in the eikonal approximation moving along a null geodesic, because such null path does not exist in Galilei space-time. The existing inclusion of electro-magnetism at the order $1/c$ made by atomic physics destroys the Galilei group and does allow a consistent definition of the Poincare' one. It is enough for experiments on the Earth, but not for going to space like in the ACES mission.

In special relativity the only intrinsic structure available to a time-like observer in Minkowski space-time is the conformal one (the light-cone): it is the locus of the incoming or outgoing rays of light. There is no notion of simultaneity, of instantaneous 3-space, of spatial distance. The light postulates say that the two-way (or round-trip; only one clock is involved) velocity of light is a) isotropic and b) constant (a standard constant c replaces

the standard of length in relativistic metrology). The one-way velocity of light between two observers depends on how their clocks are synchronized (in general is not isotropic and point-dependent). The ideal inertial frames centered on inertial observers, connected by Poincare' transformations and with the physical laws invariant in form due to the relativity principle, can be identified with Einstein's convention for clock synchronization: an inertial observer A send a ray of light at x_i^o towards the observer B; the ray is reflected towards A at a point P of B world-line and then reabsorbed by A at x_f^o; by convention P is synchronous with the mid-point between emission and absorption on A world-line, i.e. $x_P^o = x_i^o + \frac{1}{2}(x_f^o - x_i^o)$. This convention selects the Euclidean instantaneous 3-spaces $x^o = ct = const.$ of the inertial frames centered on A. Only in this case the one-way velocity of light between A and B coincides with the two-way one, c. As a consequence in relativistic metrology the Euclidean spatial length between A and B is defined as $\frac{1}{2} c (x_f^o - x_i^o)$.

However if the observer A is accelerated the convention breaks down. This is due to the fact that if we know *only* the world-line of the accelerated observer (the 1+3 point of view) the only way for defining instantaneous 3-spaces is to identify them with the Euclidean tangent planes orthogonal to the 4-velocity of the observer (the local rest frames): these planes intersect each other at a distance from A world-line of the order of the acceleration lengths of A [2] ($l = c^2/a$ for linear acceleration a and $l = c/\omega$ for rotational angular velocity ω). Therefore all the accelerated frames, centered on accelerated observers, based either on Fermi coordinates or on rotating ones will develop *coordinate singularities*, so that their instantaneous 3-spaces cannot be used for a well-posed Cauchy problem for Maxwell equations. For the rotating disk the coordinate singularity appears at a distance R from the rotation axis where $\omega R = c$ (the so-called "horizon problem"). According to the locality hypothesis for the theory of measurements [2] an accelerated observer is identified with a succession of instantaneously comoving inertial observers. See Refs[3] for a rich bibliography on these topics.

The way out from these problems is the 3+1 point of view [4], in which we assign: a) the world-line of an arbitrary time-like observer; b) an admissible 3+1 splitting of Minkowski space-time, namely a nice foliation with space-like instantaneous 3-spaces (i.e. a clock synchronization convention). This allows to define a *global non-inertial frame* centered on the observer and to use observer-dependent Lorentz-scalar *radar 4-coordinates* $\sigma^A = (\tau; \sigma^r)$, where τ is a monotonically increasing function of the proper time of the observer and σ^r are curvilinear 3-coordinates on the 3-space Σ_τ having the observer as origin. If $x^\mu \mapsto \sigma^A(x)$ is the coordinate transformation from the inertial Cartesian 4-coordinates x^μ to radar coordinates, its inverse $\sigma^A \mapsto x^\mu = z^\mu(\tau, \sigma^r)$ defines the embedding functions $z^\mu(\tau, \sigma^r)$ describing the 3-spaces Σ_τ as embedded 3-manifold into Minkowski space-time. The induced

4-metric on Σ_τ is the following functional of the embedding $g_{AB}(\tau, \sigma^r) = [z_A^\mu \, \eta_{\mu\nu} \, z_B^\nu](\tau, \sigma^r)$, where $z_A^\mu = \partial \, z^\mu / \partial \, \sigma^A$ and $\eta_{\mu\nu} = \epsilon \, (+ - --)$ is the flat metric ($\epsilon = \pm 1$ according to either the particle physics $\epsilon = 1$ or the general relativity $\epsilon = -1$ convention). While the 4-vectors $z_r^\mu(\tau, \sigma^u)$ are tangent to Σ_τ, so that the unit normal $l^\mu(\tau, \sigma^u)$ is proportional to $\epsilon^\mu{}_{\alpha\beta\gamma} \, [z_1^\alpha \, z_2^\beta \, z_3^\gamma](\tau, \sigma^u)$, we have $z_\tau^\mu(\tau, \sigma^r) = [N \, l^\mu + N^r \, z_r^\mu](\tau, \sigma^r)$ $(N(\tau, \sigma^r) = \epsilon \, [z_\tau^\mu \, l_\mu](\tau, \sigma^r)$ and $N_r(\tau, \sigma^r) = -\epsilon \, g_{\tau r}(\tau, \sigma^r)$ are the lapse and shift functions).

Let us remark that both the 1+3 and the 3+1 points of view are *non factual*; in both of them one must know an entire world-line from $\tau = -\infty$ to $\tau = +\infty$ and in the 3+1 one also a whole instantaneous 3-space.

The foliation is nice and admissible if it satisfies the conditions: 1) $N(\tau, \sigma^r) > 0$ in every point of Σ_τ (the 3-spaces never intersect); 2) $\epsilon \, g_{\tau\tau}(\tau, \sigma^r) > 0$, so to avoid the horizon problem of the rotating disk, and with the positive-definite 3-metric $h_{rs}(\tau, \sigma^u) = -\epsilon \, g_{rs}(\tau, \sigma^u)$ having three positive eigenvalues (these are the Møller conditions [5]); 3) all the 3-spaces Σ_τ must tend to the same space-like hyper-plane at spatial infinity (so that there are always asymptotic inertial observers to be identified with the fixed stars). As a consequence *rigid* rotations are forbidden in relativistic theories: see Refs.[3] for the simplest example of admissible 3+1 splitting with differential rotations. Each nice foliation has two associated congruences of time-like observers: a) the Eulerian ones having the unit normal $l^\mu(\tau, \sigma^r)$ to Σ_τ as 4-velocity; b) the rotating observers having $[z_\tau^\mu / \sqrt{\epsilon \, g_{\tau\tau}}](\tau, \sigma^r)$ as 4-velocity (this congruence is not surface-forming like the ones simulating the rotating disks).

The 4-metric $g_{AB}(\tau, \vec{\sigma})$ on Σ_τ has the components $\epsilon \, g_{\tau\tau} = N^2 - N_r \, N^r$, $-\epsilon \, g_{\tau r} = N_r = h_{rs} \, N^s$, $h_{rs} = -\epsilon \, g_{rs} = \sum_{a=1}^3 e_{(a)r} \, e_{(a)s} = \gamma^{1/3} \sum_{a=1}^3 e^{2 \sum_{b=1}^2 \gamma_{\bar{b}a} R_{\bar{b}}} \, V_{ra}(\theta^i) \, V_{sa}(\theta^i))$, where $e_{(a)r}(\tau, \sigma^u)$ are cotriads on Σ_τ, $\gamma(\tau, \sigma^r) = det \, h_{rs}(\tau, \sigma^r)$ is the 3-volume element on Σ_τ, $\lambda_a(\tau, \sigma^r) = [\gamma^{1/6} \, e^{\sum_{b=1}^2 \gamma_{\bar{b}a} R_{\bar{b}}}](\tau, \sigma^r)$ are the positive eigenvalues of the 3-metric ($\gamma_{\bar{a}a}$ are suitable numerical constants) and $V(\theta^i(\tau, \sigma^r))$ are diagonalizing rotation matrices depending on three Euler angles. The components g_{AB} or the quantities N, N_r, γ, $R_{\bar{a}}$, θ^i, play the role of the *inertial potentials* generating the relativistic apparent forces in the non-inertial frame. It can be shown [6] that the Newtonian inertial potentials are hidden in the functions N, N_r and θ^i.

Let us remark that in the ADM Hamiltonian formulation of general relativity in the York canonical basis of Ref.[7]: a) the quantities $R_{\bar{a}}(\tau, \sigma^r)$, $\bar{a} = 1, 2$, become the physical *tidal* degrees of freedom of the gravitational field (the polarizations of the gravitational waves in the linearized theory); b) the 3-volume element $\gamma(\tau, \sigma^r)$ is determined by the super-Hamiltonian constraint (the Lichnerowicz equation) in terms of the other variables; c) there is an extra inertial potential determining the allowed clock synchronization conventions, i.e. the trace $K(\tau, \sigma^r)$ of the extrinsic curvature of the non-Euclidean 3-space Σ_τ, which is a functional of

g_{AB} in special relativity and has *no Newtonian counterpart*. These results hold in a special class of globally hyperbolic, asymptotically Minkowskian at spatial infinity, topologically trivial space-time without super-translations so that the asymptotic symmetries are reduced to the ADM Poincare' group as shown in Refs.[8] and the allowed 3+1 splittings of the space-time allow to define the same type of global non-inertial frames as in special relativity. However now the equivalence principle says that global inertial frames do not exist, so that the kinematical Poincare' group is replaced by the spatio-temporal diffeonorphism group and the relativity principle with the principle of general covariance (invariance in form of physical laws). Since the absence of super-translations implies that the instantaneous 3-spaces are asymptotically orthogonal to the ADM 4-momentum, these 3-spaces are non-inertial rest frames of the 3-universe and admit asymptotic inertial observers (the fixed stars). Moreover, if we switch down the Newton constant, we get the description of the matter present in these space-times in the non-inertial rest frames of Minkowski space-time (deparametrization of general relativity) with the ADM Poincare' group collapsing in the Poincare' group of particle physics. However, in general relativity every solution of Einstein equations *dynamically* selects its preferred instantaneous 3-spaces (modulo coordinate transformations) [9]: since the whole chrono-geometrical structure, described by the 4-metric and the associated line element, is now *dynamical*, also the clock synchronization convention acquire a dynamical character. The gravitational field, i.e. the 4-metric, is not only the potential of the gravitational interaction but it also teaches relativistic causality to the other fields (it says to each massless particle which are the allowed trajectories in each point). This geometrical property is lost when the 4-metric is split in a background plus a perturbation (like in quantum field theory and string theory for being able to define a Fock space), since the chrono -geometrical structure is frozen to the one of the background; in Refs.[7, 8, 9] such a splitting is never done, since there an *asymptotic* Minkowskian background.

Let us come back to special relativity and let consider any isolated system (particles, strings, fields, fluids) admitting a Lagrangian description allowing, through the coupling to an external gravitational field, the determination of the matter energy-momentum tensor and of the ten conserved Poincare' generators P^μ and $J^{\mu\nu}$ (assumed finite) of every configuration of the system. Let us replace the external gravitational 4-metric in the coupled Lagrangian with the 4-metric $g_{AB}(\tau, \sigma^r)$ of an admissible 3+1 splitting of Minkowski space-time and let us replace the matter fields with new ones knowing the instantaneous 3-spaces Σ_τ. For instance a Klein-Gordon field $\tilde{\phi}(x)$ will be replaced with $\phi(\tau, \sigma^r) = \tilde{\phi}(z(\tau, \sigma^r))$; the same for every other field. Instead for a relativistic particle with world-line $x^\mu(\tau)$ we must make a choice of its energy sign and it will be described by 3-coordinates $\eta^r(\tau)$ defined by the intersection of the world-line with Σ_τ: $x^\mu(\tau) = z^\mu(\tau, \eta^r(\tau))$.

In this way we get a Lagrangian depending on the given matter and on the embedding $z^\mu(\tau, \sigma^r)$ and this formulation has been called *parametrized Minkowski theories* [10], [3, 4]. These theories are invariant under frame-preserving diffeomorphisms (see Ref.[11] for their first identification as the subgroup of space-time diffeomorphism of general relativity relevant for non-inertial frames), so that there are four first-class constraints (an analogue of the super-Hamiltonian and super-momentum constraints of canonical gravity) implying that the embeddings $z^\mu(\tau, \sigma^r)$ are *gauge variables*. As a consequence, all the admissible non-inertial frames are gauge equivalent, namely physics does *not* depend on the clock synchronization convention: only the appearances of phenomena change by changing the notion of instantaneous 3-space.

A particular case of this description is the *rest-frame instant form of dynamics for isolated systems* [10], [3, 4] which is done in the intrinsic inertial rest frame of their configurations: the instantaneous 3-spaces, named Wigner 3-space due to the fact that the 3-vectors inside them are Wigner spin-1 3-vectors, are orthogonal to the conserved 4-momentum of the configuration (in Ref.[6] there will be the extension to non-inertial rest frames like the ones in the formulation of canonical gravity previously quoted). In this rest frames there are only three notions of collective variables, which can be built by using *only* the Poincare' generators (they are *non-local* quantities knowing the whole Σ_τ) [12]: The canonical non-covariant Newton-Wigner center of mass (or center of spin), the non-canonical covariant Fokker-Pryce center of inertia and the non-canonical non-covariant Møller center of energy. All of them tend to the Newtonian center of mass in the non-relativistic limit. See Ref.[4] for the Møller non-covariance world-tube around the Fokker-Pryce 4-vector identified by these collective variables. As shown in Refs.[12, 13, 14] these three variables can be expressed as known functions of the rest time τ, of the canonically conjugate Jacobi data (frozen Cauchy data) $\vec{z} = Mc\,\vec{x}_{NW}(0)$ ($\vec{x}_{NW}(\tau)$ is the standard Newton-Wigner 3-position) and $\vec{h} = \vec{P}/Mc$, of the invariant mass $Mc = \sqrt{\epsilon\, P^2}$ of the system and of its rest spin $\vec{\bar{S}}$. It is convenient to center the inertial rest frame on the Fokker-Pryce inertial observer.

As a consequence, every isolated system (i.e. a closed universe) can be visualized as a decoupled non-covariant collective (non-local) pseudo-particle described by the frozen Jacobi data $\vec{z}$, $\vec{h}$ carrying a *pole-dipole structure*, namely the invariant mass and the rest spin of the system, and with an associated external realization realization of the Poincare' group. This structure implements old ideas of Ref.[15]. The universal breaking of Lorentz covariance is connected to this decoupled non-local collective variable and is irrelevant because all the dynamics of the isolated system leaves inside the Wigner 3-spaces and is Wigner-covariant. It turns out [14] that there are three pairs of second class (interaction-dependent) constraints eliminating the internal 3-center of mass and its conjugate momentum inside the Wigner

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3-spaces: this avoids a double counting of the collective variables and allows to re-express the dynamics only in terms of internal Wigner-covariant relative variables. In the case of relativistic particles the reconstruction of their world-lines requires a complex interaction-dependent procedure delineated in Ref.[13]. See Ref.[14] for the comparison with the other formulations of relativistic mechanics developed for the study of the problem of *relativistic bound states.*

In this framework it has been possible to obtain a relativistic formulation of the classical background of atomic physics, considered as an effective theory of positive-energy scalar (or spinning) particles with mutual Coulomb interaction plus the transverse electro-magnetic field of the radiation gauge valid for energies below the threshold of pair production. As shown in Refs.[16] and [14] (in Ref.[17] there will be the elimination of the internal 3-center of mass for this system), this has been possible by considering Grassmann-valued electric charges for the particles ($Q_i^2 = 0$, $Q_i Q_j = Q_j Q_i \neq 0$ for $i \neq j$). It allows a) to make an ultraviolet regularization of Coulomb self-energies; b) to make an infrared regularization eliminating the photon emission; c) to express the Lienard-Wiechert potentials only in terms of the 3-coordinates $\eta_i^r(\tau)$ and the conjugate 3-momenta $\kappa_{ir}(\tau)$ in a way independent from the used (retarded, advanced,..) Green function. All this amount to reformulate the dynamics of the one-photon exchange as a Cauchy problem with well defined potentials. Moreover there is a canonical transformation [14] sending the above system in a transverse radiation field (in- or out-fields) decoupled, in the global rest frame, from Coulomb-dressed particles with a mutual interaction described by the sum of the Coulomb potential plus the Darwin potential. Therefore for the first time we are able to obtain results, previously derived from instantaneous approximations to the Bethe-Salpeter equation for the description of relativistic bound states (see the bibliography of Ref.[16]), starting from the classical theory. Moreover, for the first time, at least at the classical level, we have been able to avoid the Haag theorem according to which the interaction picture does not exist in QFT.

Let us now consider the quantum theory.

In refs.[18] there is the quantization of positive-energy free scalar and spinning particles in a family of non-inertial frames of Minkowski space-time where the instantaneous 3-spaces are space-like hyper-planes. We take the point of view *not to quantize the inertial effects* (the appearances of phenomena): the embedding $z^\mu(\tau, \sigma^r)$ remains a c-number and we get results compatible with atomic spectra. Instead the problem of the reformulation of particle physics in non-inertial frames is unsolved due to the no-go theorem of Ref.[19] showing the existence of obstructions to the unitary evolution of a massive Klein-Gordon field between two space-like surfaces of Minkowski space-time. This problem has to be reformulated as the search of the class of admissible 3+1 splittings of Minkowski space-time admitting unitary

evolution after quantization: this would allow to check whether the hypothesis of non-quantized inertial effects is valid also in field theory (it will be a crucial point for quantum gravity!).

In Galilei space-time non-relativistic quantum mechanics, where all the main results about entanglement are formulated, describes a composite system with two (or more) subsystems with a Hilbert space which is the tensor product of the Hilbert spaces of the subsystems: $H = H_1 \otimes H_2$. This type of spatial separability is named *the zeroth postulate* of quantum mechanics. However, when the two subsystems are mutually interacting, one makes a unitary transformation to the tensor product of the Hilbert space H_{com} describing the decoupled Newtonian center of mass of the two subsystems and of the Hilbert space H_{rel} of relative variables: $H = H_1 \otimes H_2 = H_{com} \otimes H_{rel}$. This allows to use the method of separation of variables to split the Schroedinger equation in two equations: one for the free motion of the center of mass and another, containing the interactions, for the relative variables (this equation describes both the bound and scattering states). A final unitary transformation of the Hamilton-Jacobi type allows to replace H_{com} with $H_{com,HJ}$, the Hilbert space in which the decoupled center of mass is frozen and described by non-evolving Jacobi data. Therefore we have $H = H_1 \otimes H_2 = H_{com} \otimes H_{rel} = H_{com,HJ} \otimes H_{rel}$.

While at the non-relativistic level these three descriptions are unitary equivalent, this no more true in relativistic quantum mechanics, the effective quantum theory for the description of atoms as relativistic bound states of particles interacting through action-at-a-distance potentials deduced from quantum field theory (for instance the Coulomb plus Darwin potential). Once relativistic quantum mechanics is under control, we can extend it to relativistic atomic physics by quantizing also the transverse electro-magnetic field in the radiation gauge.

As it will be shown in Ref.[20], the non-local and non-covariant properties of the decoupled relativistic center of mass, described by the frozen Jacobi data $\vec{z}$ and $\vec{h}$, imply that the only consistent relativistic quantization is based on the Hilbert space $H = H_{com,HJ} \otimes H_{rel}$. We have $H \neq H_1 \otimes H_2$, because, already in the non-interacting case, in the tensor product of two quantum Klein-Gordon fields, $\phi_1(x_1)$ and $\phi_2(x_2)$, most of the states correspond to configurations in Minkowski space-time in which one particle may be present in the absolute future of the other particle. This is due to the fact that the two times x_1^o and x_2^o are totally uncorrelated, or in other words there is no notion of instantaneous 3-space (clock synchronization convention). Also the scalar products in the two formulations are completely different as shown in Ref.[21]. In S-matrix theory this problem is eliminated by avoiding the interpolating states at finite (the problem of the Haag theorem) and going the the asymptotic (in the times x_i^o) limit of the free in- and out- states. However in atomic physics we need interpolating states, and not S-matrix, to describe a laser beam resonating in a cavity and

intersected by a beam of atoms!

We have also $H \neq H_{com} \otimes H_{rel}$, because if instead of $\vec{z} = Mc\,\vec{x}_{NW}(0)$ we use the evolving (non-local and non-covariant) Newton-Wigner position operator $\vec{x}_{NW}(\tau)$, then we get a violation of relativistic causality because the center-of-mass wave packets spread instantaneously as shown by the Hegerfeldt theorem [22].

Therefore the only consistent Hilbert space is $H = H_{com,HJ} \otimes H_{rel}$, whose non-relativistic limit is the corresponding Newtonian Hilbert space, corresponding to the quantization of the inertial rest-frame instant form and englobing the notion of instantaneous Wigner 3-spaces. The main complication is the definition of H_{rel}, because we must take into account the three pairs of (interaction-dependent) second-class constraints eliminating the internal 3-center of mass inside the Wigner 3-spaces. When we are not able to make the elimination at the classical level and formulate the dynamics only in terms of Wigner-covariant relative variables, we have to quantize the particle Wigner-covariant 3-variables η_i^r, κ_{ir} and then to define the physical Hilbert space by adding the quantum version of the constraints a la Gupta-Bleuler.

The main implications for relativistic entanglement is that in special relativity the zeroth postulate for composite systems does not hold: Einstein's notion of separability is not valid since in $H = H_{com,HJ} \otimes H_{rel}$ the composite system must be described by means of relative variables in a Wigner 3-space (this is a type of weak form of relationism different from the formulations connected to the Mach principle). Due to the problem of clock synchronization and to the structure of the Poincare' group, special relativity introduces a *kinematical non-locality* and a *kinematical spatial non-separability*, which reduce the relevance of *quantum non-locality* in the study of the foundational problems of quantum mechanics. The relativistic formulation of problems like the relevance of decoherence [23] for the selection of preferred robust pointer bases and the emergence of quasi-classical macroscopic objects from quantum constituents will have to be done in terms of relative variables. Moreover, the control of Poincare' kinematics will force to reformulate the experiments connected with Bell inequalities and teleportation in terms of isolated systems containing: a) the observers with their measuring apparatus (Alice and Bob as macroscopic quasi-classical objects); b) the particles of the protocol (but now the ray of light, the "photons" carrying the polarization, move along null geodesics); c) the environment (macroscopic either quantum or quasi-classical object).

The final challenge will be a consistent inclusion of the gravitational field, at least at the

post-Newtonian level!

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